Watson and White

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BULLETIN No. 87

CORRECTION OF ECHOES AND REVERBERATION IN THE AUDITORIUM, UNIVERSITY OF ILLINOIS

BY
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And
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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN No. 87 MAY, 1916

THE CORRECTION OF ECHOES AND REVERBERATION IN THE AUDITORIUM AT THE UNIVERSITY OF ILLINOIS

BY

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PROFESSOR J. M. WHITE, Supervising Architect

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I. Introduction.

1. Preliminary.—The work described in this bulletin may be considered as a continuation of an earlier investigation on "Acoustics of Auditoriums."*

Figure 1 shows the floor plans of the auditorium under investigation. The interior approximates a sphere cut off on the lower surface by the sloping floor of the room. There is a balcony, but no gallery. The balcony projects 12 feet over the main floor at the sides and 34 feet in the rear. The stage is built out into the room instead of being set back behind a proscenium arch as originally designed, the stage house having been omitted to reduce the cost of the building.

The domed ceiling is supported on four equal arches, and the side walls above the gallery are double curved surfaces. The limited appropriation for the building made it impossible to embellish the surfaces of the walls and ceiling, and therefore, they were left practically plain, which increased their power to reflect sound and cause echoes. There are no windows in the room, the daylight lighting being exclusively through a ceiling light 30 feet in diameter in the center of the dome.

The results set forth in the previous bulletin are briefly as follows. A systematic investigation of the acoustical properties of the Auditorium at the University of Illinois was carried on for several years. "Cut and try" methods of cure were avoided. It was shown by theory and experiment that the usual acoustical faults in a room are due first, to a reverberation, or undue prolongation of sound, and second, to echoes; both of these defects being caused by the reflection of sound from the walls. Various methods of cure were considered,—the effect of padding and paneling the walls, the possible advantage of installing wires† and sounding boards,‡ and finally, the action of

*Bulletin No. 73 of the Engineering Experiment Station, University of Illinois.

†"Inefficiency of Wires as a Means of Curing Defective Acoustics of Auditoriums." Science, Vol. 35, p. 833. 1912.

‡"The Use of Sounding Boards in an Auditorium." Physical Review, Vol. 1 (2), p. 241, 1913. Also The Brick Builder, June, 1913.

the ventilating system.* The conclusion was drawn that the most effective cure lay in padding the walls with materials which absorb sound.

An experimental diagnosis of the acoustical properties of the Auditorium was made. This was done by tracing the path pursued by a small bundle of sound when it was sent in a definite direction and noting what became of it after reflection. Several methods of tracing sound were tried before a suitable one was found. A ticking watch backed by a reflector, or a metronome enclosed in a box having a directed horn gave definite data. However, a hissing arc light with a parabolic reflector was much more satisfactory and gave conclusive results. Enough data were secured in this way to show the general behavior of the sound in the room and also to indicate how the chief echoes were set up.† Attempts were then made to secure satisfactory acoustics by hanging curtains and draperies at critical points suggested by the diagnosis. This result was finally secured by suspending four large pieces of canvas in the dome.

From the acoustical standpoint, the Auditorium was then in a much improved condition. The canvas, however, was very unsightly and did not accord with the architectural features of the room. It was therefore proposed that the materials used to correct the acoustics be installed in such manner as to remedy this fault. It was also proposed at this time to install a pipe organ, to decorate the interior of the room, and to change the lighting system.

2. *Object of the Bulletin.*—The object of this bulletin is to describe the changes that were made in the Auditorium to carry out the proposals just mentioned, and especially to show how the acoustical properties were modified.

II. Preliminary Acoustical Investigation.

It was desired that the materials used to correct the acoustics be installed in such manner as to conform with the architectural features of the Auditorium. This introduced a new problem since in the provisional cure the canvas sheets in the dome hung with very little conformity to the curvature of the walls. A further complication appeared when it was found by calculation that the amount of material necessary to correct the reverberation was insufficient to pad all the

*"Air Currents and Acoustics of Auditoriums." Engineering Record. Vol. 67, p. 265, 1913.

†"Echoes in an Auditorium." Physical Review, Vol. 32, p. 231, 1911.

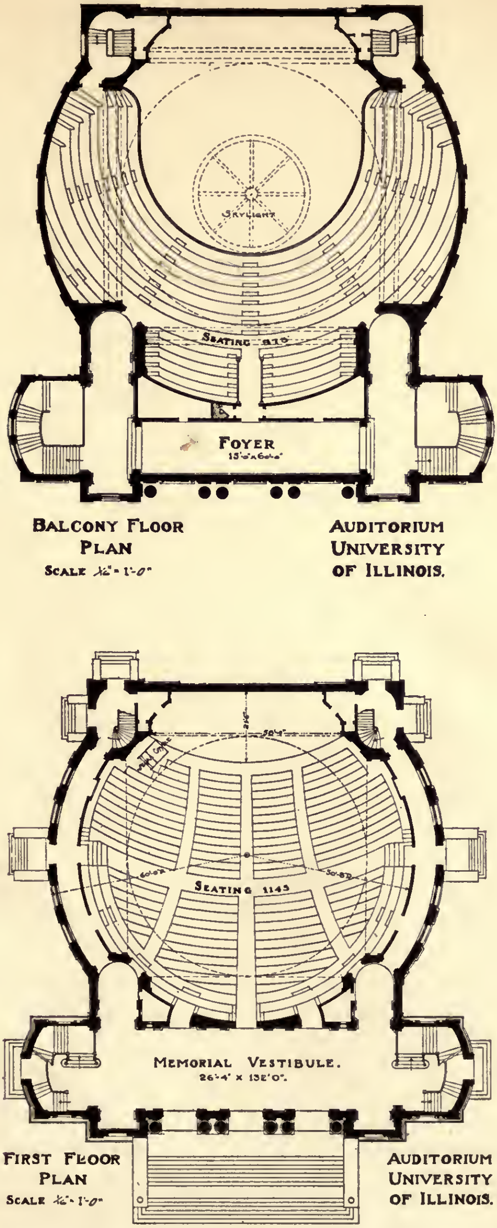

Fig. 1. Floor Plans Showing Interior of the Auditorium at the University of Illinois which was Corrected for Echoes and Reverberation.

walls that produced echoes. It was desirable to eliminate the echoes, but it was regarded as risky to install too much sound absorbing material, owing to the danger of making the Auditorium too dead for sound.

Because of these difficulties it was decided to carry on further experiments and to secure more data before deciding on the final cure. Accordingly, one large curved wall was covered with strips of one-inch hair felt, 30 inches wide, placed vertically and 30 inches apart so as to leave bare spaces between them. This arrangement was satisfactory for several reasons; it did not change the curvature of the wall; it used only half the amount of material necessary to cover the entire wall; and because of diffraction and interference effects, it was theoretically more efficient in breaking up the reflected sound than if the same material were spread continuously over the whole surface. Although encouraging, the results were not so marked as expected in diminishing the echoes.

On the basis of this experiment, plans were made for covering other walls in a similar way, except that the hair felt was to be mounted on wooden ribs built out from the wall surface. Such an installation seemed more likely to break up the incident sound than the first plan of mounting the hair felt snugly against the wall. The sound wave on striking these outer felt strips would suffer partial reflection and change of phase, while the remaining portion of the sound would pass through the open spaces and be spread out by diffraction and reflection from the walls. The hair felt strips would oppose the incident and reflected waves, thus breaking up the original sound and diminishing its intensity and possibility of producing echoes.

Because the scaffolding erected for the use of the workmen interfered with the passage of sound waves, the efficiency of this method of placing the felt could not be tested step by step as the material was mounted. The test was deferred, therefore, until the installation was completed. In the meantime the pipe organ was installed, the interior was redecorated, and the lighting system changed, so that only the combined effect of all these factors on the acoustics could be investigated.

III. Modifications of the Interior of the Auditorium.

3. *Installation of the Pipe Organ.*—The organ was mounted in a unique way by dividing it into two parts and placing them in lofts 24 feet above the ends of the stage with a distance of 75 feet between centers. This arrangement placed the organ at a considerable distance

above the audience. The absence of any vertical surface between the lofts and the audience room prevented any visible arrangement of the organ pipes, but the necessary free exit of the sound was provided for by the construction of ornamental plaster grills covering the pendentives on either side of the stage. (See Fig. 2.)

FIG. 2. VIEW TOWARD THE STAGE SHOWING THE GRILL WORK FOR FREE PASSAGE OF SOUND FROM THE CONCEALED ORGAN. THE ORGAN CONSUL IS SHOWN TO THE LEFT. CARPET IS REMOVED FROM STAGE IN PREPARATION FOR AN ORCHESTRA CONCERT

4. *Method of Mounting Hair Felt.*—The hair felt was mounted on thin furring strips which were bent to fit the curvature of the surfaces. The dome above the arches and the double curved side walls and single curved rear wall above the balcony were padded in this way. The felt was mounted in vertical strips on the west side wall as shown in Fig. 3. Fig. 4 shows the wall after the material was installed and decorated.

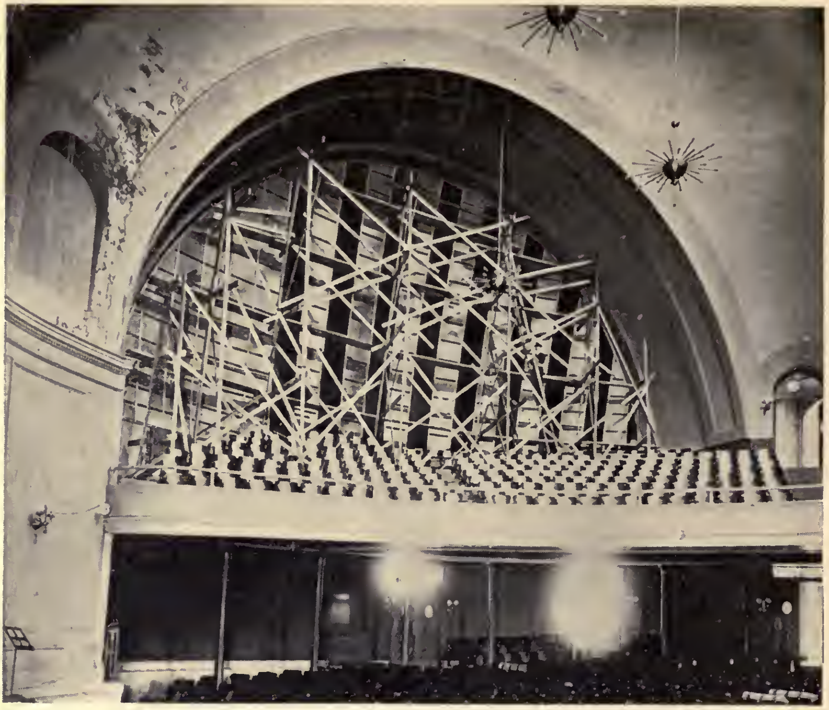

FIG. 3. PHOTOGRAPH SHOWING THE MOUNTING OF THE HAIR FELT IN VERTICAL STRIPS. THE MATERIAL WAS FASTENED TO THIN FURRING STRIPS WHICH COULD BE BENT TO CONFORM TO THE CURVATURE OF THE SURFACE

On the east balcony wall the felt was mounted on wooden ribs so that it stood concentric with the plaster surface at a distance of one foot. Eighteen inches below the edge of the skylight in the dome radial strips of felt which approached the wall until they touched at the crown of the arches, were mounted on wooden ribs. (Fig. 5.) The hair felt used was the Akustikos Felt developed especially for correction of acoustical faults by the H. W. Johns-Manville Company under the direction of Professor Sabine.

Before the changes were made in the Auditorium, Professor Sabine visited the building at the invitation of President James. After this visit, he wrote to President James as follows: "If such confirmation of the results of Professor Watson's investigation is necessary, please permit me to assure you that you will obtain an excellent effect from following out his suggestions in all detail." The final installation was

FIG. 4. PHOTOGRAPH SHOWING THE SIDE WALL OF FIG. 2 WHEN COMPLETED. A REP OF SUITABLE COLOR WAS STRETCHED OVER THE ENTIRE SURFACE AND DECORATED. IT WAS NECESSARY FOR THE FREE PASSAGE OF THE SOUND THAT THE MATERIAL USED IN DECORATING SHOULD NOT CLOSE THE PORES OF THE REP

modified somewhat from the original plans, but the general features were maintained.

5. *The Decoration and the Lighting System.*—The modification of the lighting system involved the elimination of the suspended fixtures. The wall brackets were retained, but the main lighting was changed to a semi-indirect system with reflectors above the arches and around the skylight. An ivory tone was selected for the basic color in the redecoration. Ornamentation was stenciled and painted on the various walls and surfaces to give a unified effect. With the exception of the ornamental borders the rep covering the padded surfaces was left its natural color. The difference between the old and new interiors is shown in Figs. 6 and 7. The modifications relieved the auditorium of its cheerless. barn-like interior.

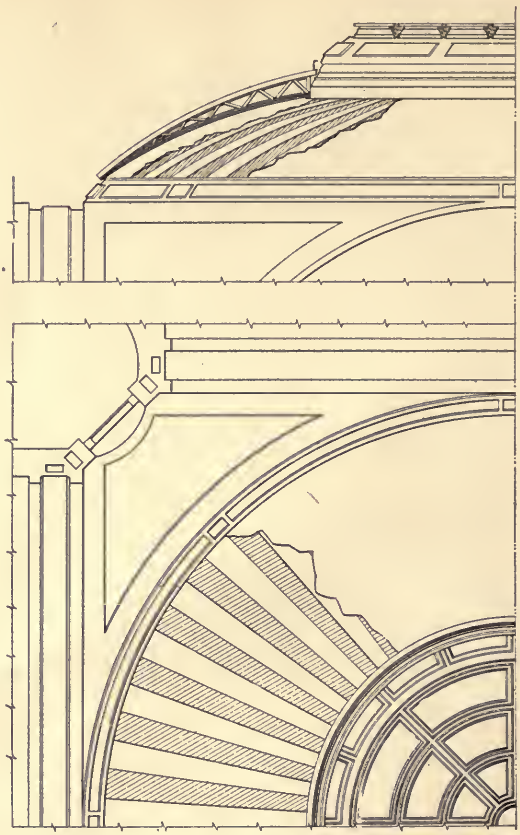

FIG. 5. DIAGRAM SHOWING THE DOME SURFACE WITH WOODEN RIBS SEPARATING THE HAIR FELT IN RADIAL STRIPS. THIS FALSE CEILING ARRANGMENT WAS THOUGHT MORE EFFECTIVE FOR ABSORPTION OF SOUND THAN IF THE MATERIAL WERE MOUNTED SNUGLY AGAINST THE SURFACE

IV. FINAL ACOUSTICAL INVESTIGATION.

The remodeled Auditorium has been tested under varied conditions for music and speaking, and popular opinion has pronounced the acoustics satisfactory. A speaker with a moderate voice can be heard distinctly by auditors in the most distant seats. The music of the new pipe organ, according to experts, is satisfactorily rendered. The room is also suited for orchestra music, though for this case, it has been found advantageous to follow the usual custom of leaving the wooden floor of the stage bare of carpet so as to reenforce the sound from the instruments.

While the Auditorium has proved to be generally satisfactory, a detailed investigation of the acoustical effects secured by the modification of the room was thought desirable. A request was made, accordingly, that auditors report any echoes or acoustical disturbances however slight they might be. About a dozen replies were received, and on the basis of these and other considerations, a systematic investigation was undertaken.

Fig. 6. Photograph showing Auditorium before changes were made

The acoustical results, beneficial and otherwise, may be anticipated by considering the changes made. According to Sabine, the hair felt installed would reduce the reverberation. This would also eliminate echoes if installed on certain surfaces in accordance with the analysis; but, since the amount of material used to correct the reverberation was insufficient to cover all the walls, acoustical defects might still be set up by the unpadded surfaces, especially by the pendentives. The pipe organ, by generating musical sounds that emerged through the pendentives in the dome, might introduce new acoustical disturbances. The openings made in the surfaces of two of the pendentives for the passage of the organ music would reduce the general

FIG. 7. PHOTOGRAPH SHOWING NEW INTERIOR OF AUDITORIUM. THE SUSPENDED LIGHTING FIXTURES WERE REMOVED, THE INTERIOR REDECORATED, AND THE REAR WALL IN THE ALCOVE PADDED

reverberation and would also diminish echoes. The changes in the decoration and in the lighting system would produce little effect.

6. *Investigation of Echoes.*—Tests were made in several ways to determine the presence of echoes. The opinion offered by auditors that the echoes had generally disappeared was, of course, the most satisfactory evidence. One test was made by talking through a megaphone toward different walls (Fig. 8). The sound was generated inside a small house and its direction of propagation controlled by two megaphones, one being pointed toward an observer and the other toward a wall which previously gave echoes. No distinct echo could be obtained by speaking simultaneously into the two megaphones. The ticks of a metronome produced very little additional effect, but when a sharp intense metallic sound was tried, echoes were obtained from the unpadded walls but only faint responses from the padded walls. The intense hissing sound of an arc light backed by a parabolic reflector gave more pronounced results. It showed that the padded walls produced a marked effect in reducing the intensity of the sound.

FIG. 8. PHOTOGRAPH OF STAGE SETTING SHOWING EXPERIMENTAL HOUSE WITH MEGAPHONES USED FOR TESTING ECHOES

The effect of the unpadded pendentives in the rear dome surface is shown in Fig. 9. The cone of incident sound received by each pendentive is small and, after reflection, spreads over a large area. It was therefore anticipated that little disturbance would result. This prediction was not entirely correct since the echoes reported by auditors, so far as could be ascertained, came from these two walls. An echo was perceptible when the speaker faced directly toward one of these pendentives so that the profile of his face was seen by an auditor seated at one side of the auditorium. The direct sound coming to the auditor was then diminished while the reflected sound was augmented, thus producing an echo.

Other unpadded walls, notably the side walls under the balcony, still set up concentrations of sound. Thus, an observer at A, Fig. 10, can hear not only the direct sound from the speaker, but also the portion that is concentrated by reflection from B. He does not hear an echo because the time interval between the direct and reflected sounds is too short to enable his ear to detect them separately. The result is

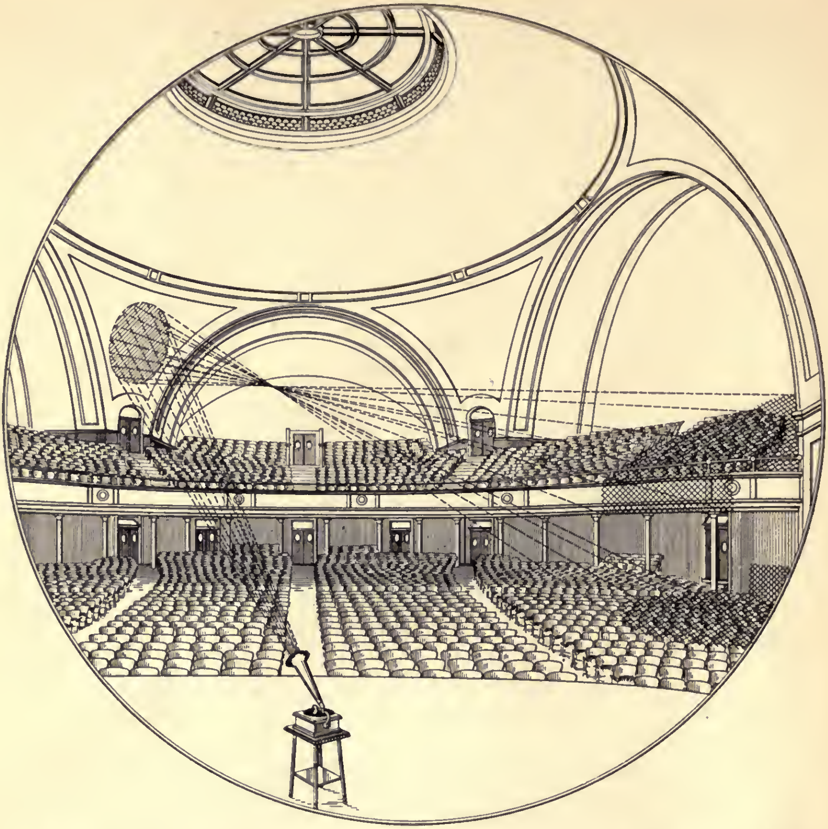

FIG. 9. DIAGRAM SHOWING THE REFLECTION OF SOUND FROM THE UNPADDED PENDENTIVE IN THE REAR WALL. ECHOES SET UP BY THIS WALL CAN OCCASIONALLY BE NOTED

much the same as if his neighbor on the side toward the wall were to say the words of the speaker in his ear at the same time that he received them from the speaker. The auditor realizes that something is peculiar about the sound but usually does not understand the cause of the trouble. An auditor at C, however, may get an echo when the speaker faces the point D.

7. *Investigation of the Reverberation.*—By means of Sabine's formula and coefficients of absorption* the time of reverberation of the Auditorium was found and a calculation was made to determine the amount of sound absorbing material necessary to correct the fault. The following tabulation shows the method employed:

*American Architect, 1900.

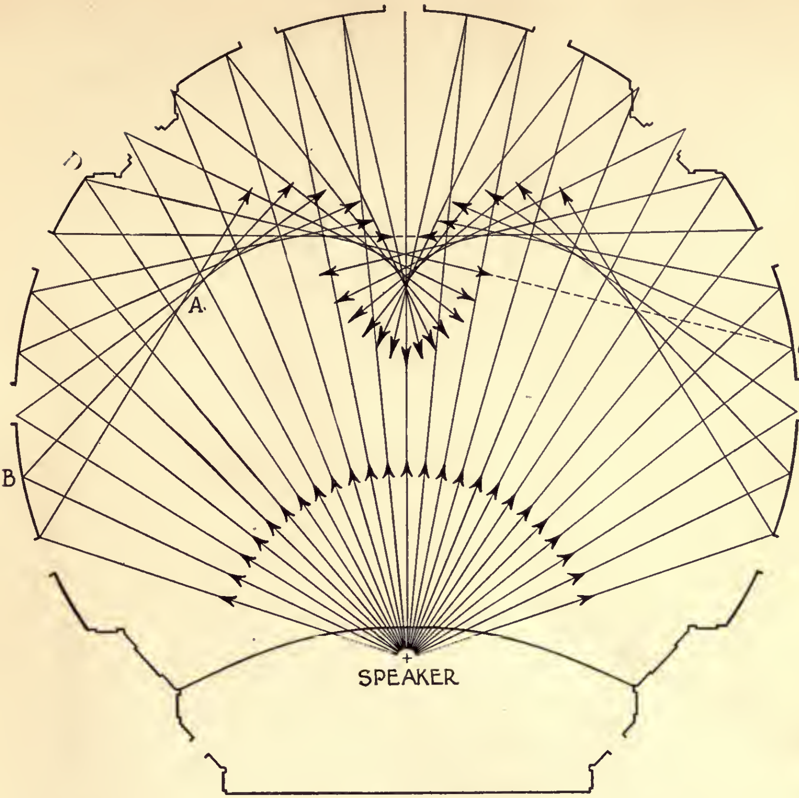

FIG. 10. PLAN OF AUDITORIUM SHOWING CONCENTRATION OF SOUND BY THE WALLS UNDER THE BALCONY

Material	Exposed Area in sq. meters	Coeff. of Absorption	Total Absorption
Plaster on lath	2000	0.0330	66.0
Plaster on tile	510	0.0250	13.0
Wood work	1630	0.0610	99.0
Glass	83	0.0270	2.3
Cocoa matting	145	0.0200	2.9
Wood seats	2150 seats	0.0082	17.7
			201
Average audience	1200 people	0.44	527
		Total	728

Volume of room..........12000 cubic meters.

Substituting these data in the formula $t=0.164\ V\div a$, in which t is the time of reverberation, V the volume of the room and a the total absorbing power, the following equation for the empty room is obtained:

$t=0.164\times12000\div201=9.8$ seconds.

When an audience of 1200 people is present,

$t=0.164\times12000\div728=2.7$ seconds.

This value is too great for good acoustics and a reverberation results. To correct the fault, absorbing material should be added until the time of reverberation is reduced to about 1.8 seconds; this value having been found satisfactory for halls as large as the Auditorium when used for both music and speaking.

The amount of Akustikos Felt needed to carry out the plans already described was 3315 square feet. This was less than the area necessary for felt mounted snug against the wall since the coefficient of absorption is greater when the felt is mounted out from the wall.* Calculations, which allowed for the sound absorbing power of the felt and the other alterations in the Auditorium indicated that the time of reverberation would be reduced to about 1.90 seconds with 1200 people present.

V. Discussion and conclusions.

The Auditorium fulfilled the theory held many years ago by Lord Rayleigh* that a large room with hard, non-porous walls and with few windows has a prolonged resonance, and that the best chance of improvement lies in padding the walls and ceiling with sound absorbing materials. Thus, the installation of hair felt in the Auditorium reduced the reverberation; the amount of reduction being calculated in advance by Sabine's† formula and constants of absorption.

The amount of hairfelt necessary to correct the reverberation was insufficient to cover all the walls, and it was found that some of these unpadded surfaces still produced echoes. This action was anticipated in part from the general considerations discussed by Rayleigh‡ in which the possibility of reflection of sound was shown to depend on the positions of the source and receiver of sound, and also upon the size and form of the wall compared with the wave length of the incident sound.

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*Sabine. Architectural Quarterly of Harvard University, p. 22, March, 1912.

*Theory of Sound, Vol. 2, pp. 287 and 351.

†American Architect, 1900.

‡Theory of Sound, Vol. 2, p. 28?.

The installation in an auditorium of considerable sound absorbing material eliminates the objectional condition of satisfactory reverberation being wholly dependent on the sound absorbing power furnished by an audience. This means that rehearsals without an audience can be conducted satisfactorily and that a speaker addressing a small audience is not obliged to contend with a distressing reverberation.

The theoretical advantages in absorbing and breaking up sound waves when hair felt is mounted out from a wall instead of placed snugly against the surface do not appear to be so great as expected. Observers listened to sounds reflected from both types of surface and concluded that a surface having the hair felt mounted out from the wall was more efficient. The conclusions, however, should be checked by quantitative, instrumental measurements since the ear is inaccurate in its estimation of the comparative intensities of different sounds.* It appears that the felt is more effective when mounted out from the wall, but there is some question whether or not the advantages secured justify the additional expense of installation and the greater risk of fire.

The music of the pipe organ emerging in large volume from the pendentives in the dome introduced concentrations of sound different from those set up when the source of sound was on the stage. This made it desirable to pad other walls in addition to those requiring padding for the single source of sound.

The effect of the organ music confirmed one conclusion set forth by Jäger†; namely, that the strength of the source of sound for good acoustics should be in correct proportion to the volume of the room. It appears that the Auditorium is too small for loud organ music since the sound in this case becomes unpleasantly intense. On the other hand, it appears that the volume is fairly well suited for softer organ music and for a weak source of sound, such as a speaker with a moderate voice. In this connection Jäger contends that an auditorium is limited in its acoustical possibilities; that if a room is too large, it is impossible to make it satisfactory for weak sources of sound. He points out also that the problem of correcting faulty acoustics must include a consideration of intensity of sound as well as of reverberation; that is, the variable factors at command, the volume and absorbing power of the room and the source of sound, must be so propor-

*Rayleigh, Scientific Papers, Vol. II, p. 132.

†"Zur Theorie des Nachhals," Sitzungsberichten der Kaiserl. Akademie der Wissenschaften in Wien. Matem-naturw. Klasse; Bd. CXX, Abt. IIa, Mai, 1911.

tioned as to give not only a suitable reverberation but also an acceptable intensity of sound. He discusses the limitations in obtaining this desired result.

Another deduction made by Jäger which applies rather directly to the Auditorium is that the ratio S/W should be large for good acoustics, in which S is the total surface of walls, furniture, and fixtures struck by the sound and W is the volume of the interior. Theoretically, this ratio is smallest for a sphere, and, since the Auditorium approximates a hemisphere, the excessive reverberation might have been predicted.

Reverberations and echoes were corrected simultaneously by installing a suitable amount of hair felt on the walls which produced echoes. To locate these walls, a new method was developed in which the source of sound was an arc light as explained earlier in this bulletin.

The investigation showed that curved walls are worse acoustically than plane walls since they produce undesirable concentrations of sound and echoes. It also appears that the openings in the pendentives for the organ music and the ventilation openings act similarly to open windows and thus reduce reverberation and diminish echoes.

One acoustical disturbance which was not corrected was that due to talking and walking in the foyer and on the stairs immediately outside the Auditorium. The sounds of footsteps and the reverberation caused by loud talking and accidental noises in the foyer could be reduced by covering the stairs and foyer with a yielding material, such as cork and by padding some of the walls.

It is apparent from this discussion that the means employed to correct the acoustics, as exemplified by this complex problem, were based upon established scientific principles and this investigation and others of like nature have served, to a large extent, to dispel the mystery surrounding the action of sound in auditoriums.

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(This is an addition to the bibliography published with Bulletin No. 73 on "Acoustics of Auditoriums.")

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